REPORT ON KNOYDART FEASIBILITY STUDY AND PMP FLOW BATTERY PROTOTYPE DEVELOPMENT PROJECT

ENSURING FUTURE ENERGY SECURITY OF KNOYDART

LOCAL ENERGY CHALLENGE FUND – PHASE 1

CONTENTS

1. EXECUTIVE SUMMARY

Power Migration Partners (PMP) has developed a novel flow battery energy storage system and are planning a full scale installation to solve the current problems of the Knoydart community. At present the Knoydart electrical grid uses power from a hydro-electric power scheme (hydro scheme) and a diesel generator during peak hours, which has a high levelized cost of energy (LCOE). But the hydro scheme does not get fully utilized during off peak hours. Future demand increase will force Knoydart Renewables (KRL) to run the diesel generator at all times to avoid blackouts. But a suitably designed energy storage system will allow KRL to remove the diesel generator from operation by storing hydro power during off peak times and using stored energy during peak times. In addition, a grid tied Smart energy storage system can be used to provide grid stability.

A prototype flow battery was developed during this feasibility study. Load and generation profiles identified in the Knoydart energy feasibility study were used to build a scaled down test bed which can mimic the Knoydart power generation system and electric loads. The ELTUN prototype was tested using this test bed to confirm the functional compatibility. A programmable Xantrex power supply was used to mimic the generator and a resistive load bank controlled by MOSFETs was used as the load. Load and generation profiles were controlled by a LABVIEW interface. This setup proved that the ELTUN flow battery can stabilise the Knoydard grid.

As part of this feasibility study, PMP carried out a detailed analysis of the Knoydart power generation and distribution system considering increased future energy demand and availability of emergency power. The technical and financial analysis indicated that an energy storage system with 400 kWh of output energy capacity and 75 kW of output power would best suit the Knoydart micro-grid. Table 1 below shows a comparison of the calculated LCOE at present, if the future demand increase is provided by the hydro scheme and diesel generator and finally, if the future demand is provided by the hydro scheme and the ELTUN flow battery.

System Description	Levelized Cost of Energy
Present energy generation with hydro scheme and diesel generator	13.7 p/kWh
Increased future demand with hydro scheme and diesel generator	16.3 p/kWh
Increased future demand with hydro scheme and ELTUN flow battery	12.4 p/kWh

Table 1: LCOE (levelized cost of energy) for a range of energy supply options

The main benefits the Knoydart community would gain from adding the ELTUN flow battery to their micro-grid are as follows:

- Reduction of LCOE
- Grid stabilization due to the quick response speed and two way communication ability of the smart flow battery system

- Avoid use of the expensive diesel generated power and use power generated by the hydro turbine during off peak hours
- Emergency backup power during a grid failure
- Reduced carbon emissions
- Opportunity to develop Green tourism
- Future potential to use the flow battery liquid to power inland vehicles.

2. INTRODUCTION

The projected doubling of world energy consumption by 2050 , coupled with the need for low emission sources of energy has led to an increased demand for efficient renewable energy technologies. However, the use of electricity generated from these intermittent, variable renewable energy sources requires efficient electrical energy storage (EES) to bridge the gap between generation and demand. In the UK, application of energy storage technologies could potentially generate total system savings of £20bn/year by 2050 . In addition it is estimated that business opportunities created by innovations in EES could contribute up to £25 billion to the UK economy by 2050 .

At present, wide spread use of EES has been limited due to the unavailability of economical, efficient and effective energy storage technologies. Among all energy storage technologies, electrochemical energy storage technologies will be the leading EES systems in the future due to their scalability and versatility.

Power Migration Partners (PMP) has developed a novel flow battery energy storage technology called the **El**ectron **Tun**nelling Flow battery (ELTUN Flow Battery). The system is economical, easily scalable, has a long cycle life, can be manufactured locally and is energy dense compared to existing systems. This Lithium-Sulphur technology was developed using state of the art material technologies and an innovative power electronic converter topology. An independent intellectual property audit had been carried out for this technology confirming its novelty and industrial significance[1].

The energy storage system is particularly applicable to community renewable energy generation systems with variable resource e.g. wind/solar farms. Given the changes to the current renewable energy policy, this has the potential to make community renewable energy developments more commercially viable while reducing carbon emissions. In this project, a feasibility study was carried out based on a remote community system in the Knoydart peninsula. This community is isolated from the national grid and supplies all of its energy locally from a hydro-electric power scheme (hydro scheme) supplemented by a diesel generator. Knoydart Renewables is a community owned company that was established after the community purchased the Knoydart peninsula. They have managed and operated the Knoydart micro-grid for 15 years and would like to try out new technologies that will optimise the power generation from their hydro-electric power scheme (hydro

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[1] : *Annex 9- IP Audit Summary of the PMP ELTUN Flow Battery*

scheme), and solve the existing challenges of this aging system. Knoydart Renewables is the energy generation and distribution arm of the Knoydart Foundation.

The present energy generation and distribution system in Knoydart has numerous technical and financial problems. Therefore it was decided to explore possibilities of resolving these problems by a joint project carried out by PMP and Knoydart Renewable. A feasibility study and a small scale prototype build was planned including a complete technical, financial analysis and a detailed business case.

After securing necessary funds, PMP and Knoydart renewables carried out the planned feasibility study to identify the best size of the PMP energy storage system, cost and actual benefits of integrating a suitably sized energy storage system to the Knoydart micro grid. In parallel a proof of concept prototype of the PMP energy storage system was developed by PMP as a part of this project.

3. INTRODUCTION TO THE BUSINESS

Redox flow batteries or cells are a type of secondary batteries, whereby liquid electrolytes are circulated through a reaction cell separated by a thin membrane to store energy. A redox reaction occurs in each cell and ion transfer through the membrane creates a current flow. This is a scalable energy storage technology currently been looked at by a number of organizations around the world such as EnerVault, REDT, Unienergy technologies, GEFC and General Electric (GE).

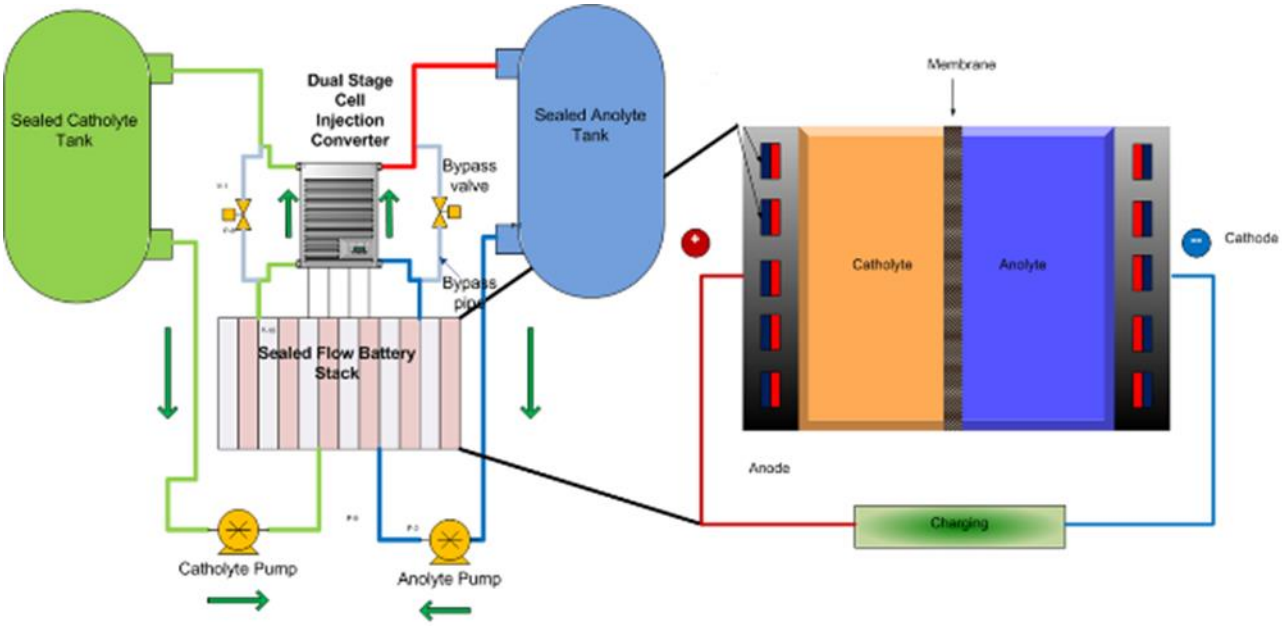

Figure 1: PMP Flow Battery Storage System with expanded view of a single flow battery cell.

PMP has come up with a novel and improved redox flow battery technology (ELTUN) based Smart Energy Storage System, which can revolutionize the future of electrical energy storage. ELTUN will have unique properties which makes it attractive to many electrical energy storage related applications. A basic representation of the ELTUN is shown in Figure 1 above. The main components of the system are

I. Flow battery storage system using economical chemical reduction-oxidation couples. The ELTUN design enables the use of low cost reactants without decreasing system efficiency.

II. An integrated power electronic platform which works hand-in-hand with the flow battery, which uses a Dual Stage Cell Injection (DSCI) Power Converter. This enables efficient energy harness from renewable sources.

III. Thermo-siphon supported flow circulation systems, which keeps reactants in a suitable temperature range while enabling use of a smaller heat-sink for power semiconductor devices.

IV. Control and communication electronic system enabling internet integration. This sub system converts the whole setup in to a Smart storage device. As described earlier, a Smart converter or a Smart Inverter by definition has a digital architecture, bidirectional communications capability and robust software platform.

V. Pumps, Pipes, structural components, switchgear other auxiliaries.

The system will allow renewable energy systems to store produced energy and export it to the final consumer in an intelligent manner. ELTUN has a flexible power electronic system and a modular nature, which enables it to cater for other industrial and commercial energy storage requirements other than renewable energy systems. Some of its unique benefits are lower cost, high efficiency, ability to extract and export power at low voltage input levels, weather based control, easy expandability and Smart energy export capability.

In this project the main focus is building a proof of concept prototype which is particularly suitable for the Knoydart power grid and carrying out a comprehensive feasibility study to identify technical and financial requirements of an energy storage system designed for the Knoydart peninsula.

4. PRESENT ENERGY GENERATION AND DEMAND OF KNOYDART

The Knoydart peninsula is completely isolated from the mainland power grid and has its own micro-grid powered by a hydro scheme and supplemented by a diesel generator. The hydro scheme was restricted to 180 kW and ran under-capacity at off-peak times. A recent dam and pipeline upgrade had increased the power up to 220 kW. Upgrading the existing grid infrastructure to accommodate more generation and meet peak demand would involve significant capital expense. Currently, there are power black-outs when demand exceeds supply from the hydro scheme due to seasonal variations. The expected average energy demand increase of a human population is calculated to be around 1-2% according to world energy demand statistics[2]. At this rate the repetitive peak demand values of the Knoydart community will exceed 220 kW in a few years and the present power supply system will not be able to meet this continuous peak demand. Since the present system uses a

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[2] : *International Energy Agency – Key World Energy Statistics*, 2014

mechanical governor with a relatively slow response rate, the system is not able to respond to short, high peak power demands.

Figure 2 : Generation control system of the present hydro generator which uses a mechanical governor

The community currently supplements their energy demands by using a diesel generator in parallel with the hydro generator. This is undesirable as the community wishes to minimise their carbon emissions and remove the need for expensive transport of diesel from the mainland. In addition, the storage of diesel is an environmental and safety hazard. Therefore, one of the aims of this project is to minimize the use of this diesel generator which is used mainly during peak demand periods. The energy storage system would also provide energy during a transmission system failure, for example, power disruptions have occurred in the past during storms when trees fell over main transmission line.

Figure 3 : Drawing of the Knoydart power transmission grid

An in-depth analysis of the energy demand and generation profiles of the community was carried out by collecting one year of hourly demand and generation data, operation costs, diesel fuel costs, distribution systems details and environmental data such as rainfall data.

4.1 PRESENT ENERGY GENERATION AND DEMAND MODEL

A comprehensive system model was developed using HOMER micro-grid simulation software. The model included the following input data;

1. Hourly consumption data for one year - extracted from logged data
2. Hourly power generated by the hydro scheme - extracted from logged data
3. Hourly power generated by the diesel generator - extracted from logged data
4. Hydro scheme maintenance costs
5. Diesel generator maintenance and fuel costs
6. Hydro scheme technical data including head, design flow rate, pipe loss and response speeds
7. Hydro scheme financial data - investment and replacement costs
8. Diesel generator financial data - investment, replacement and operational costs
9. Transmission system data including transmission losses
10. Sensitivity details e.g. rainfall variation, patterns of peak power demand

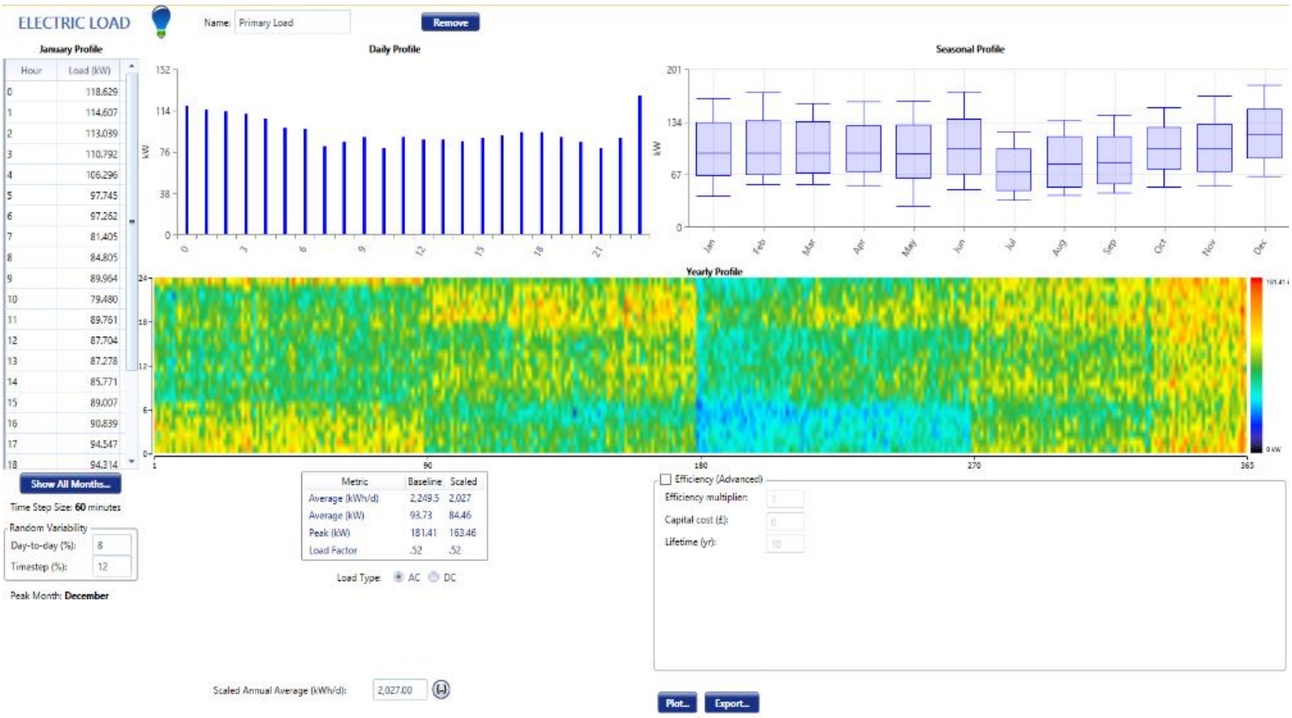
All models other than the simulation model for the present load consumption were optimized for the lowest LCOE and the best performance.

4.2 SIMULATION FOR THE PRESENT GENERATION AND DEMAND

The simulation model for the present grid consist of 4 main components.

i. The diesel generator
ii. Hydro turbine,
iii. Transmission grid
iv. Consumer loads.

The simulation for the present generation and demand showed that the Knoydart electricity supply system annually supplies close to 740,000 kWh of energy to consumers (average of 2,027 kWh/day). The data shown in Figure 4 below includes provisions for transmission losses. A grid model simulation was carried out and the results were compared with the actual present-day parameters such as LCOE, annual energy generation, energy demand and the number of blackouts. The results of the simulation model were in agreement with actual parameters therefore the grid model proved to be a valid baseline for sizing a suitable energy storage system.



Name: Primary Load

January Profile

Hour	Load (kW)
0	118.629
1	114.607
2	113.039
3	110.792
4	106.296
5	97.745
6	97.262
7	81.405
8	84.805
9	89.964
10	79.480
11	89.761
12	87.704
13	87.278
14	85.771
15	89.007
16	90.839
17	94.547
18	94.314

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): 8
Timestep (%): 12

Peak Month: **December**

Metric	Baseline	Scaled
Average (kWh/d)	2,249.5	2,027
Average (kW)	93.73	84.46
Peak (kW)	181.41	163.46
Load Factor	.52	.52

Load Type: ● AC ○ DC

Scaled Annual Average (kWh/d): 2,027.00

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost (£): 0
Lifetime (yr): 10

Figure 4 : Consumer load modelling for present load

5. FUTURE DEMAND INCREASE AND ENERGY COSTS

The Knoydart future demand was modelled considering a future demand increase that was calculated and agreed with Knoydart Renewables (KRL). Demand data was collected and discussions were held with community members to accurately calculate the future demand increase. According to world energy demand statistics[3], we can safely assume that the demand increase in Knoydart is around 1%. The historical annual energy demand increase has been fluctuating between 1%-2% in Knoydart according to Knoydart energy demand statistics[4]. Over 25 years this would be a cumulative increase of 28% compared to the present level. As an average value, a 14% future demand increase was considered in this study.

5.1 HYDRO SCHEME SUPPLY ONLY

Figure 5: Load profile for estimated increased future demand below shows the load profile generated using the predicted future energy demand. Initially the system was simulated only with the hydro system supplying the community energy demand. In this case it was seen that there is a clear capacity shortage and the energy supply system becomes very unstable. Therefore, the hydro scheme alone cannot supply the increased demand profile. This means that without an energy storage system, KRL will need to increase the diesel based energy generation in future to meet the energy demand. In addition, this implies that KRL will have to keep the diesel generator running part-load at all times to avoid grid instability in the future.

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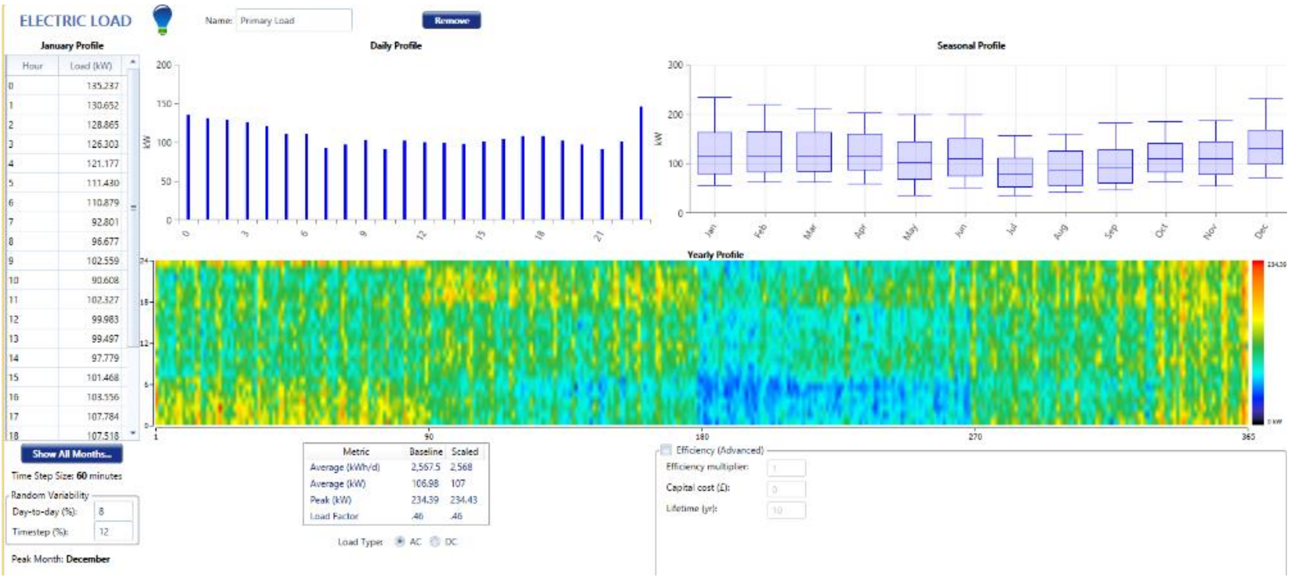
[3] : *International Energy Agency – Key World Energy Statistics*, 2014

[4] : Knoydart energy demand statistics – Prepared by Angela Williams



Name: Primary Load

January Profile

Hour	Load (kW)
0	135.237
1	130.652
2	128.865
3	126.303
4	121.177
5	111.430
6	110.879
7	92.801
8	96.677
9	102.559
10	90.608
11	102.327
12	99.983
13	99.497
14	97.779
15	101.468
16	103.556
17	107.784
18	107.518

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 8

Timestep (%): 12

Peak Month: **December**

Metric	Baseline	Scaled
Average (kWh/d)	2,567.5	2,568
Average (kW)	106.98	107
Peak (kW)	234.39	234.43
Load Factor	.46	.46

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost (£): 0

Lifetime (yr): 10

Figure 5: Load profile for estimated increased future demand

Figure 6 below shows the AC primary load profile in the top graph and the capacity shortage in the bottom graph. This shows that the highest capacity shortage is close to 60 kW (peak value). On average, there will continuously be a 10-20 kW capacity shortage meaning that the electrical grid will be unstable.

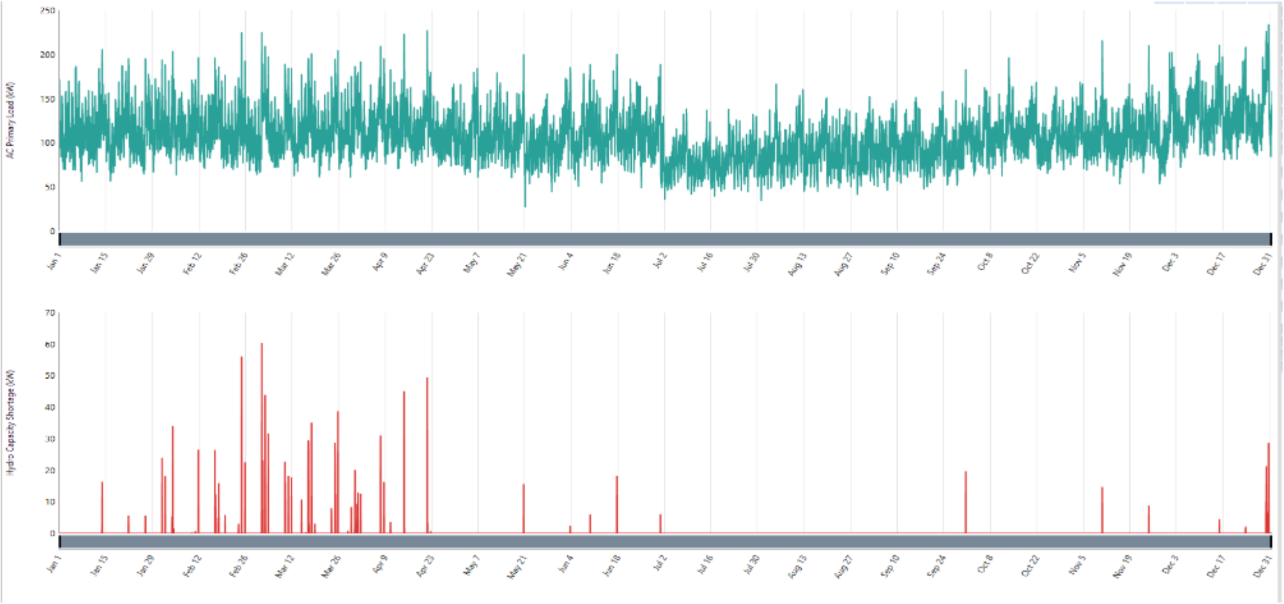


Figure 6: AC primary load profile (top) and the capacity shortage (bottom).

5.2 HYDRO – DIESEL GENERATOR HYBRID SYSTEM

The previous section showed that there will be a capacity shortage during peak hours for the increased demand profile if the hydro scheme alone is used. Therefore, alternative generation or energy storage options must be used to stabilize the power supply. The first alternative available is to use the diesel generator in tandem with the hydro turbine. Even though the diesel generator will not run efficiently in part load mode, the system will work. However, the diesel generator will not be able to meet any sudden demand peaks if it is not already operational at that time.

Total net present cost	£1,973,346
LCOE	0.163 £/kWh

Table 2 below shows the LCOE for the hydro-diesel hybrid system to supply the increased demand profile. Due to the increased use of diesel, the cost per unit goes up to as high as 16.3 p/kWh[5].

The parameters and assumptions used for this scenario are as follows:

- Project life time: 25 years
- Discount rate: 8%
- Inflation rate: 1 %
- Capital investment Cost: £450K (Source: Energy Mutual)
- System operational expenditure: £80K/annum
- Diesel cost: 80p/L (including transportation and storage)
- Diesel Generator cost: £30K

Total net present cost	£1,973,346
LCOE	0.163 £/kWh

Table 2: LCOE with hydro-diesel system in tandem

During off-peak hours, the hydro turbine alone will be able to supply the load and the diesel generator can be shut down. If the hydro system is supplying off peak loads and there is a sudden increase in peak

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[5] : *Annex 17- Case Simulation - Hydro and Diesel used for future demand*

demand, the diesel generator will not be able to get grid synchronized quickly enough to supply that load and there will be a blackout.

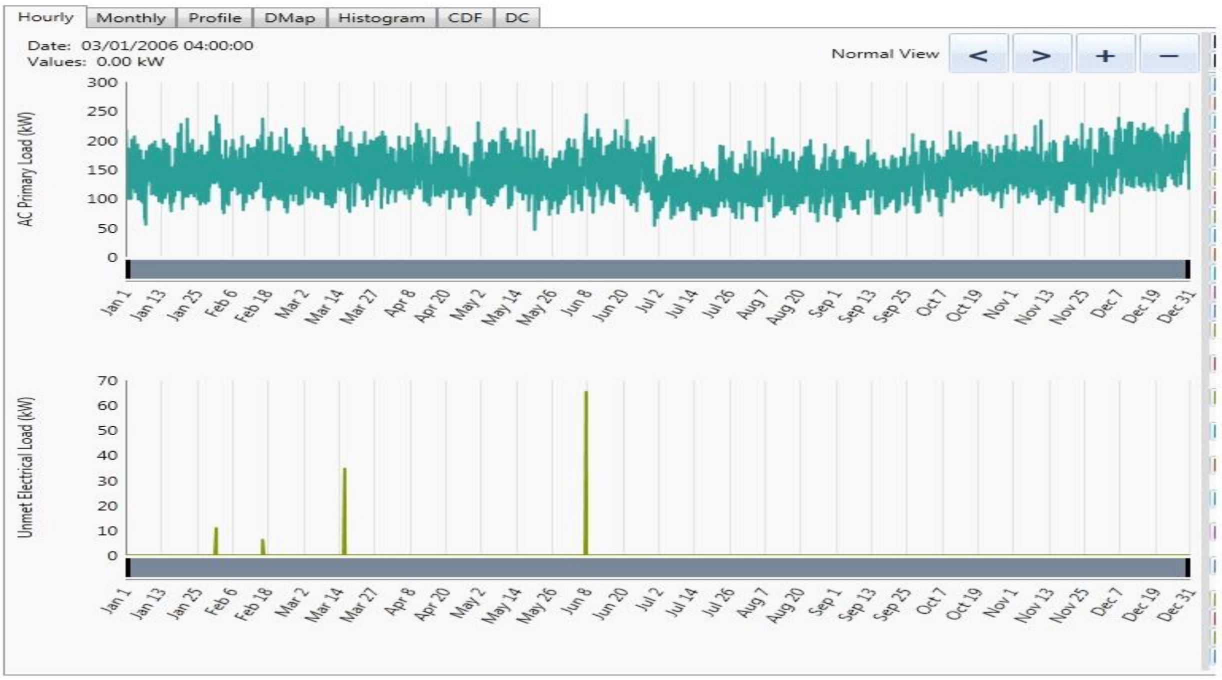

Figure 7: AC primary load profile (top) and capacity shortages (blackouts) (bottom) when hydro-diesel hybrid system is used for future demand

Figure 7 above shows the potential of blackouts when the hydro-diesel hybrid system is used to cater for the future power demands of Knoydart. These potential blackouts take place in the spring and summer months. This is because the generator will not be running during the summer time and therefore will not be able to respond to sudden demand increases. The diesel generator will be running during winter and autumn due to higher energy demand and therefore would be able to absorb peaks in demand.

5.3 HYDRO – BATTERY HYBRID SYSTEM

Following a series of sensitivity studies and theoretical calculations, it was found that an energy storage system with 400 kWh of output capacity and 75 kW of output power would best suit the Knoydart micro-grid. The energy storage system would be charged during off peak hours and the power would be released during peak demand periods. The power electronics will be continuously grid tied to the 415 AC system and will act as a negative load by releasing power when the power demand passes a set threshold value. This would stabilise the grid and reduce the load on the hydro generator, decreasing the occurrence of black-outs. The ELTUN flow battery system will monitor grid voltage, frequency and communication input using power line communication equipment (PLC) in order to improve the control strategy.

The following sections show how the output capacity and power output of the energy storage system was identified.

5.3.1 ELTUN flow battery power output requirement

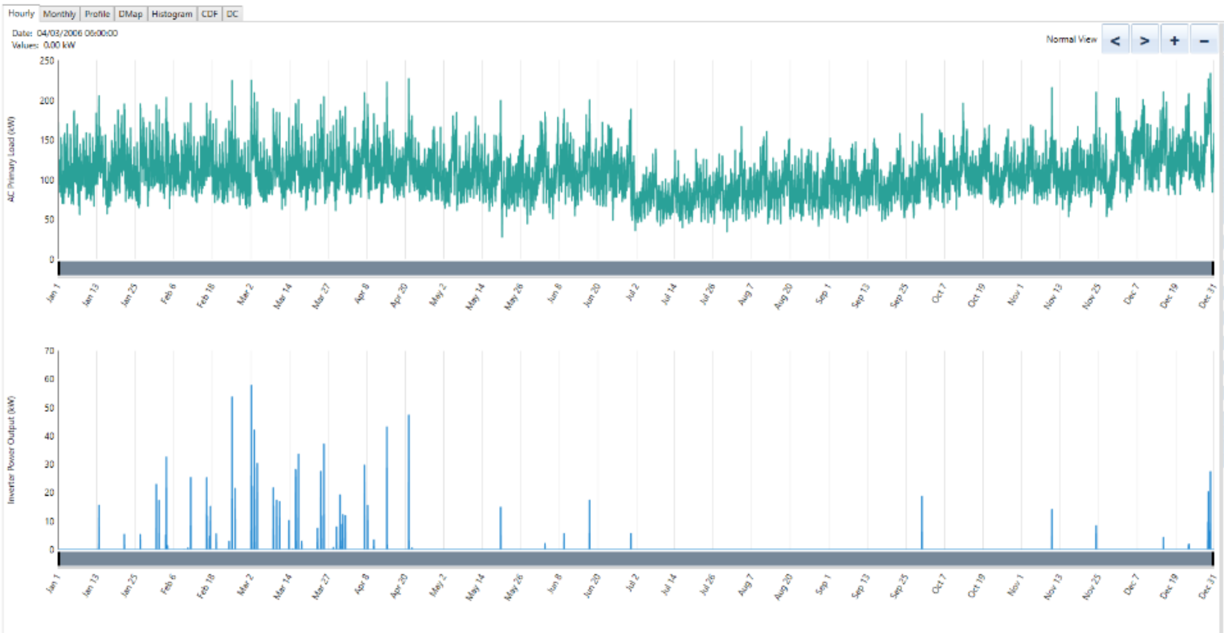

Figure 8 : AC primary load profile (top) and maximum power output required by the energy storage system to stabilize the power distribution system (bottom).

The top graph in Figure 8 above shows the total electrical load served by the Knoydart power system. The bottom graph shows the maximum energy output required by the energy storage system to stabilize the power distribution system. It can be clearly seen that the required power level is below 60 kW. With a 25% safety margin to capture instantaneous peak demands, a 75 kW would be a reasonable size for the power output of the flow battery. The flow battery will start injecting power in to the grid before the demand reach the maximum capacity of the hydro turbine, which will consequently reduce the load on the hydro turbine.

5.3.2 ELTUN flow battery energy output requirements

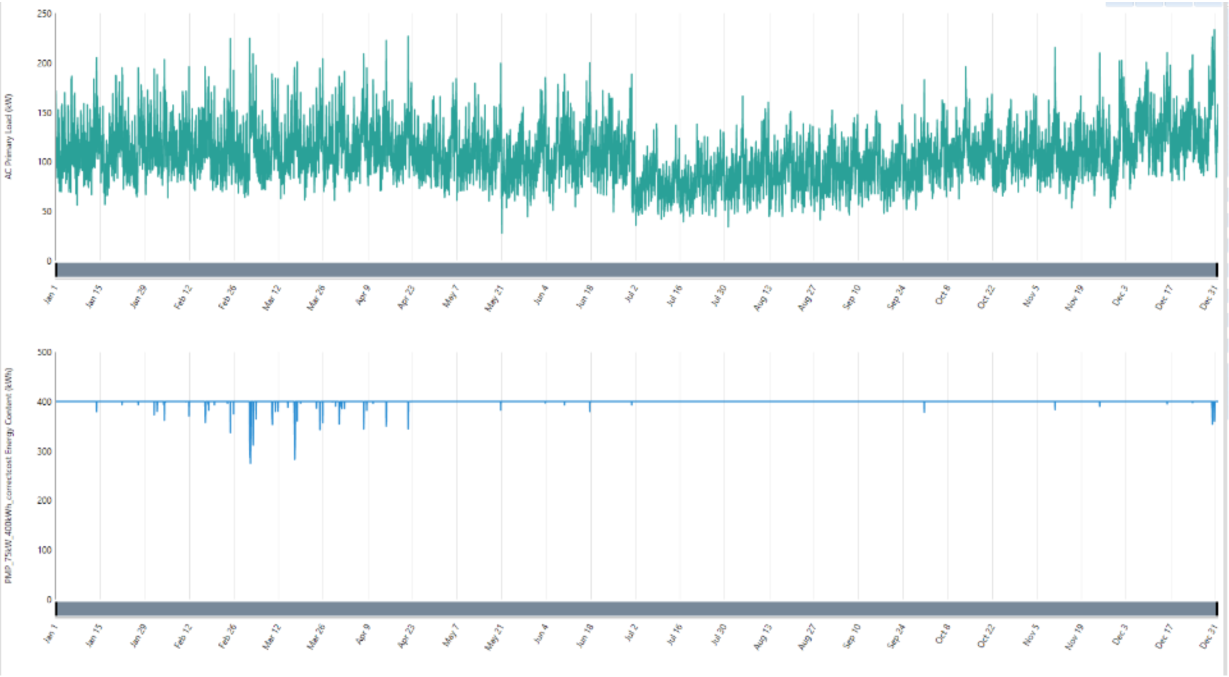

Figure 9: Energy output of the energy storage system (bottom graph)

Figure 9 shows the required energy output of the energy storage to keep the grid stabilized while catering for the load demand. It can be clearly seen that a 400 kWh system would easily cater for the demand. The flow battery is a deep cycle battery and can discharge down to 5 % level.

5.3.3 State of Charge and Off-peak battery charging

Figure 10 below shows the ELTUN flow battery's state of charge. It can be seen that the system has the ability to keep the battery charged the majority of the time. Therefore, in case of a transmission line failure, the energy storage system would be able to provide power for critical loads for a short period of time.

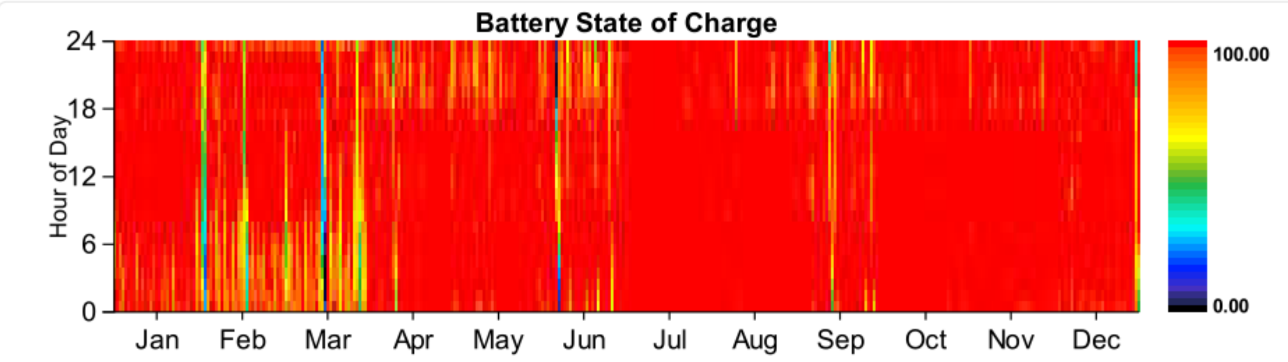

Figure 10: Battery state of charge during the year (red=100% charged)

6. FINANCIAL OUTLOOK

A LCOE calculation has been completed for the case where Knoydart will get an ELTUN flow battery energy storage system with an initial cost investment of £450k, this is the loan amount taken to carry out the dam upgrade work in 2015. KRL is paying off another loan taken out for past dam upgrade work carried out during the period 2002-2005.

6.1 LCOE CALCULATION FOR HYDRO-BATTERY HYBRID SYSTEM

The financial parameters used for this scenario are as follows:

- Project life time: 25 years
- Discount rate: 8%
- Inflation rate: 1%
- Capital investment Cost: £450K (Source: Kyle Smith)
- System operational expenditure: £80K/annum
- Diesel cost: 80 p/L (including transportation and storage)
- Battery maintenance cost: £10K/annnum

Total net present cost	£1,507,377
LCOE	0.124 £/kWh

Table 3 : LCOE if the initial investment is the actual loan amount serviced by KRL- taken out for the dam upgrade project

From this analysis it can be seen that the use of the ELTUN flow battery gives the lowest LCOE compared to the hydro-diesel hybrid cost of 16.3 p/kWh. The price of energy can be set in a reasonable range for KRL to maintain a positive cash flow. From Table 3, it can be seen that the actual LCOE is around 12.4 p/kWh[6], if the hydro system is considered as a free asset to KRL.

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[6] : *Annex 18- Case Simulation Battery and Hydro for future demand*

7. PROTOTYPE DEVELOPMENT OF THE ELTUN FLOW BATTERY

7.1 OBJECTIVES

Main purpose of this project is to develop an efficient, scalable and cost effective smart energy storage system, providing key benefits to its end users. In addition it is intended to carry out few tasks which will support future commercialization aspects of the product.

7.1.1 Measurable Technical Objectives

1. Build a proof of concept flow battery cell stack within 7 months of project initiation to facilitate testing.
2. Thoroughly test the novel method of reducing cross contamination of redox species across ion exchange membrane using magnetic bipolar plates. The target is to come up with quantitative results within 2 months after completing the proof of concept model.
3. Test the thermo-siphon assisted electrolyte pumping and heating system which uses semiconductor heat dissipation as the energy source. This should reduce the pump energy consumption and make the system more efficient by bringing the solution temperature closer to the efficient working temperature window. In addition, this should effectively reduce power semiconductor heat-sink size and pump size reducing the cost. This will be tested 3 months after completing the proof of concept model.
4. Build and test the novel Dual Stage Cell Injection (DSCI) converter at low voltage input conditions which should start power generation under low source voltages. Power electronics have to work hand in hand with the flow battery to enable this.
5. Identification of redox couples with optimum performance, which will be suitable for the weather conditions in Knoydart.

7.2 TECHNICAL TASKS AND TECHNICAL ACHIEVEMENTS

7.2.1 Building of a battery stack

A proof of concept battery stack was built within the planned period of the project. The complete system was modelled using a 3D modelling software to correctly design stack components, piping and internal flow paths.

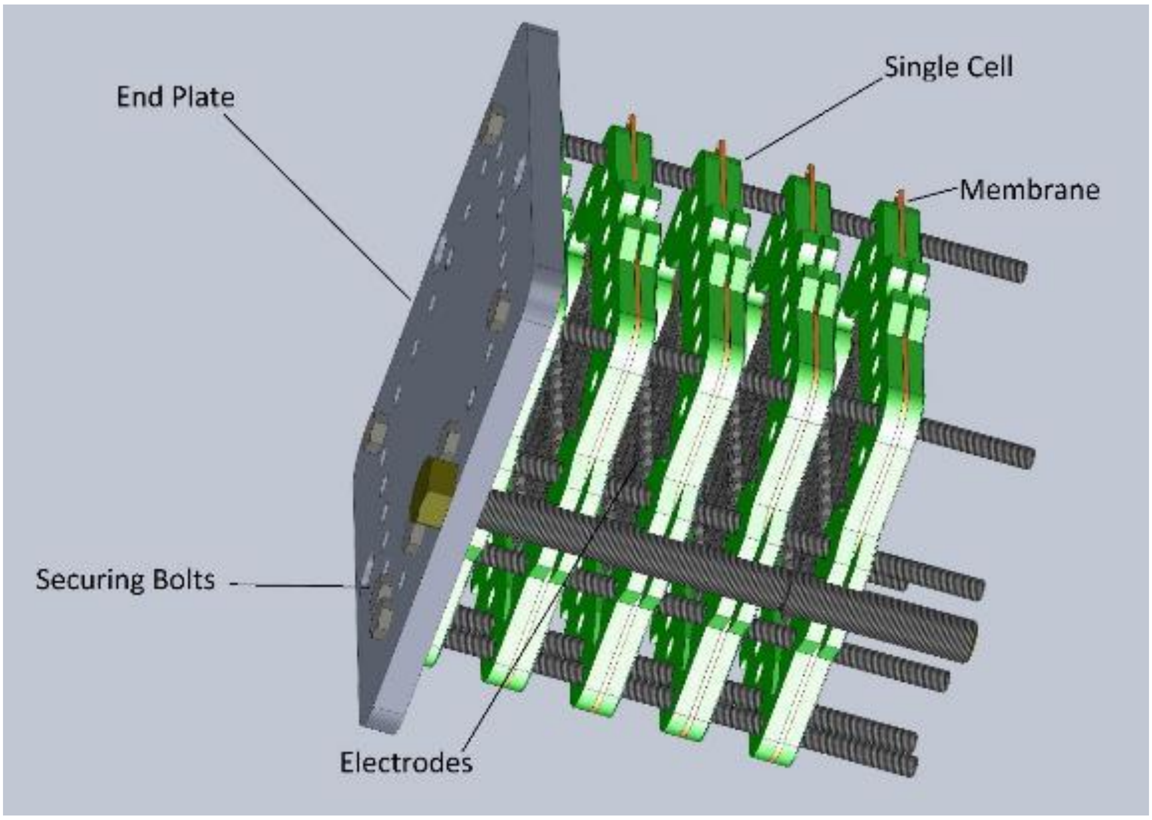

Figure 11: Main assembly with and exploded view of the flow stack

Figure 11 above shows an exploded view of the flow stack 3D cad model. Effective electrolyte flow through the stack was optimized using this cad model. It was used for many other design tasks such as pipe work selection, flow connector selection, etc.

Several tests were carried out before finalizing material. Correct material had to be used for many components such as end plates, cell separators, sealing gaskets, membranes, electrode current collectors and other parts of the stack. All parts were tested for mechanical and chemical stability. Tests were carried out whenever necessary and experts were consulted for confirmation.

Figure 12 : Acetal cell separator section

Figure 12 above shows acetal cell separator sections which were manufactured using waterjet cutting process, after modelling it in 3-D. This section is a novel design which allows low resistance flow of fluids and which can be configured to use one or two different electrolytes.

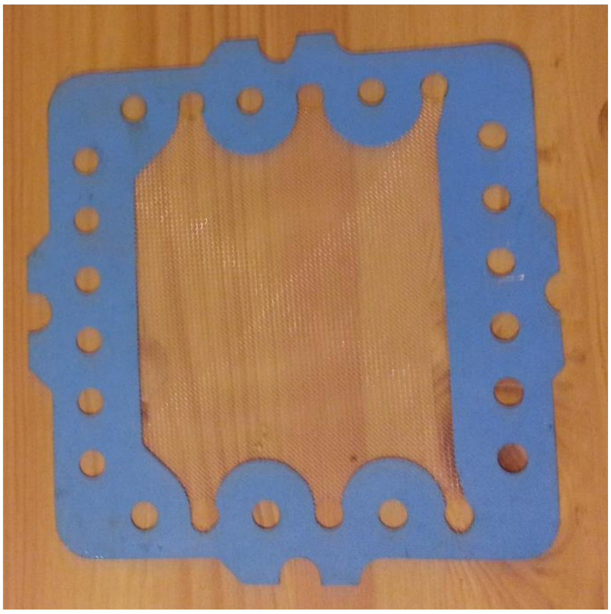

Figure 13 : Tested rubberized separator

Various material were tested as separators. Stability with different electrolytes, solvents, additives and stability under different temperature levels were investigated. Figure 13 and Figure 14 shows couple of gasket material which were tested. GP paper gasket was selected after testing due to its resistance to wide variety of chemicals and due to its thermal stability.

Figure 14 : GP Paper Gasket

In the similar manner suitable material for current collectors were tested by trying out different parts.

Figure 15: Aluminium electrode current collector coated with graphene nano platelets

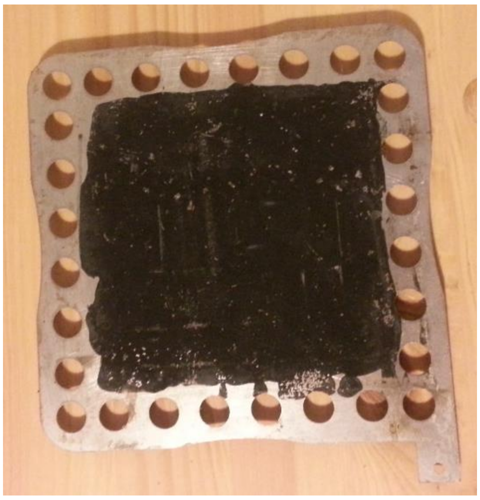

Figure 16: Steel electrode current collector coated with graphene nano platelets

Figure 16 and Figure 15 above shows the steel and aluminium current collectors tested in the design. It was found that for a particular family for anolytes, steel current collectors were suitable and aluminium current collectors were suitable for a particular type of catholytes. In the final design, a combination of steel and aluminium current collectors, which were coated using graphene nano platelets were used. Other than these main components, significant amount of design effort were put in to identify suitable material for bolt insulation, end plate material, tube material and flow connector material.

Figure 17 : Initial battery testing setup used for material and electrolyte stability testing

Figure 17 above shows a battery testing setup used for preliminary testing. This simple system setup helped the team to conduct accelerated testing and reduce preparation time for each test carried out.

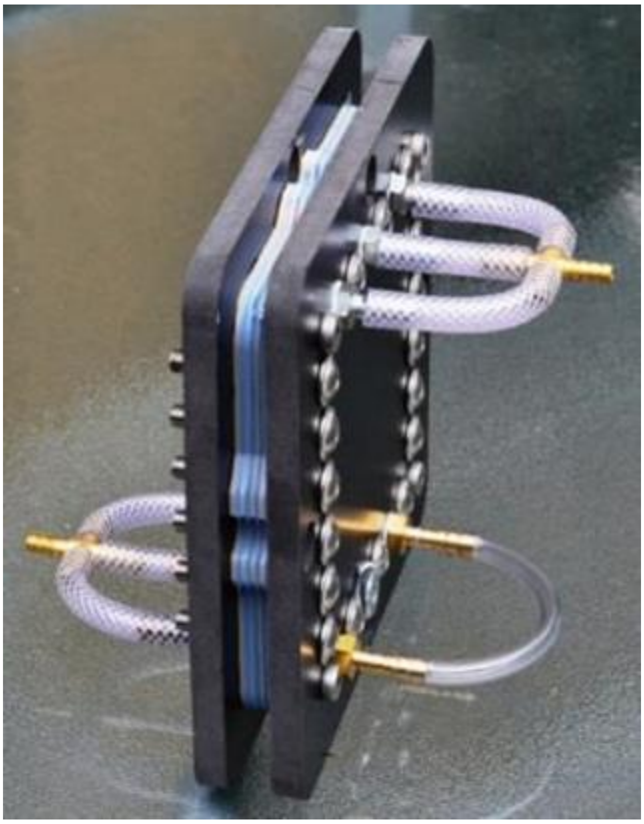

Figure 18 – Picture of the test battery stack

Figure 18 above shows a picture of a test battery stack assembled using the optimized cell components. Due to the muti-path flow architecture, the flow resistance was minimized in this design. Using the extensive tests carried out for material selection, it was possible to identify economical and durable material to be used in the battery stack.

7.2.2 Method of reducing cross contamination of redox species across ion exchange membrane using magnetic bipolar plates

In this experiment, the concept of reducing cross contamination of redox species across ion exchange membrane using magnetic bipolar plates was tested. Graphite electrodes with magnetic inserts were prepared by pressing graphite in a mould and baking it (Partial sintering). Graphite electrodes with same material were made without magnet inserts to be used as the pilot apparatus to compare performance or the effect of magnetic bi-polar plates.

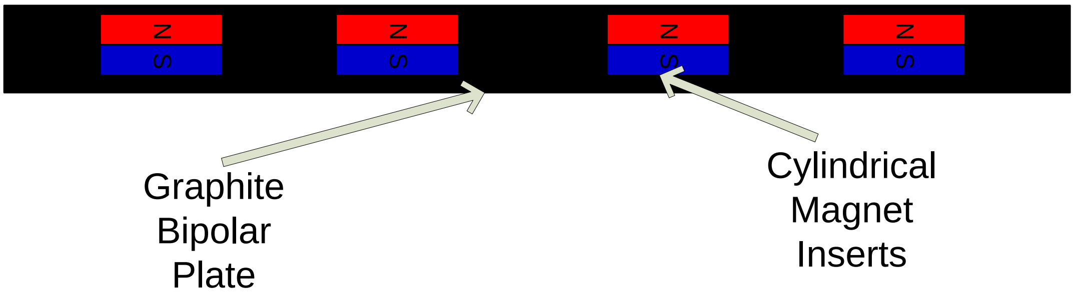

Figure 19 : Concept of magnet inserts in the graphite electrode.

Figure 19 shows the concept of magnet inserts in the graphite electrode. It was known that certain electrolytic species created by mixed electrolytic media are often paramagnetic. Paramagnetic molecules have unpaired electrons and will be attracted by magnetic fields. It was assumed that this effect will help to reduce cross mixing of species, which is a major problem in modern flow battery designs.

Figure 20 : Graphite Electrode with Magnetic inserts

Figure 20 above is a bipolar graphite plate constructed using small neodymium magnet inserts. This was moulded using appropriate binders to maintain conductivity. Since neodymium is a good conductor of electricity, inserting them in the graphite electrode does not affect the conductivity.

Response of a molecule or a species in a solution to a magnetic field is quantified by a measure called molar magnetic susceptibility. For diamagnetic species, molar magnetic susceptibility is very low and temperature independent. For paramagnetic species, molar magnetic susceptibility is much higher. We measure para-magnetism of species generated using this measure to ensure that we have correct electrolytes.

Ions are monopoles and will either move along or against an electric field, depending on the polarity of the ion. Most paramagnetic species are dipoles and will always be attracted into a magnetic field, independent of the direction of the magnetic field vector. These dipoles will experience a resultant magnetic force if a magnetic field gradient is present. Because electrochemistry involves in single electron transfer events, the majority of electrochemical reactions should result in a resultant change in the magnetic susceptibility of species near the electrode.

As explained above, tests were carried out using modified electrodes and unmodified electrodes. Two types of electrolytes with paramagnetic species were used in the tests. Porous polypropolene base ion conductive membranes were used to obtain a slightly increased cross mixing, which will enable us to analyse samples in order to quantify the percentage cross contamination in a single half-cell. To conduct the experiment, electrolyte were run through the cell for a period of an hour and a small quantity of electrolyte was obtained from the tank every minute and stored carefully in micro containers. Analytical methods were used to quantify cross contamination percentage in each sample bottle.

Figure 21 below shows the results of using magnetic bipolar electrodes and using same electrolytes with a pilot cell without magnetic bipolar plates. According this plot, the difference between cross contamination levels are less than 1%. This is a very small percentage change to justify the cost of material which have to be used obtain this small difference.

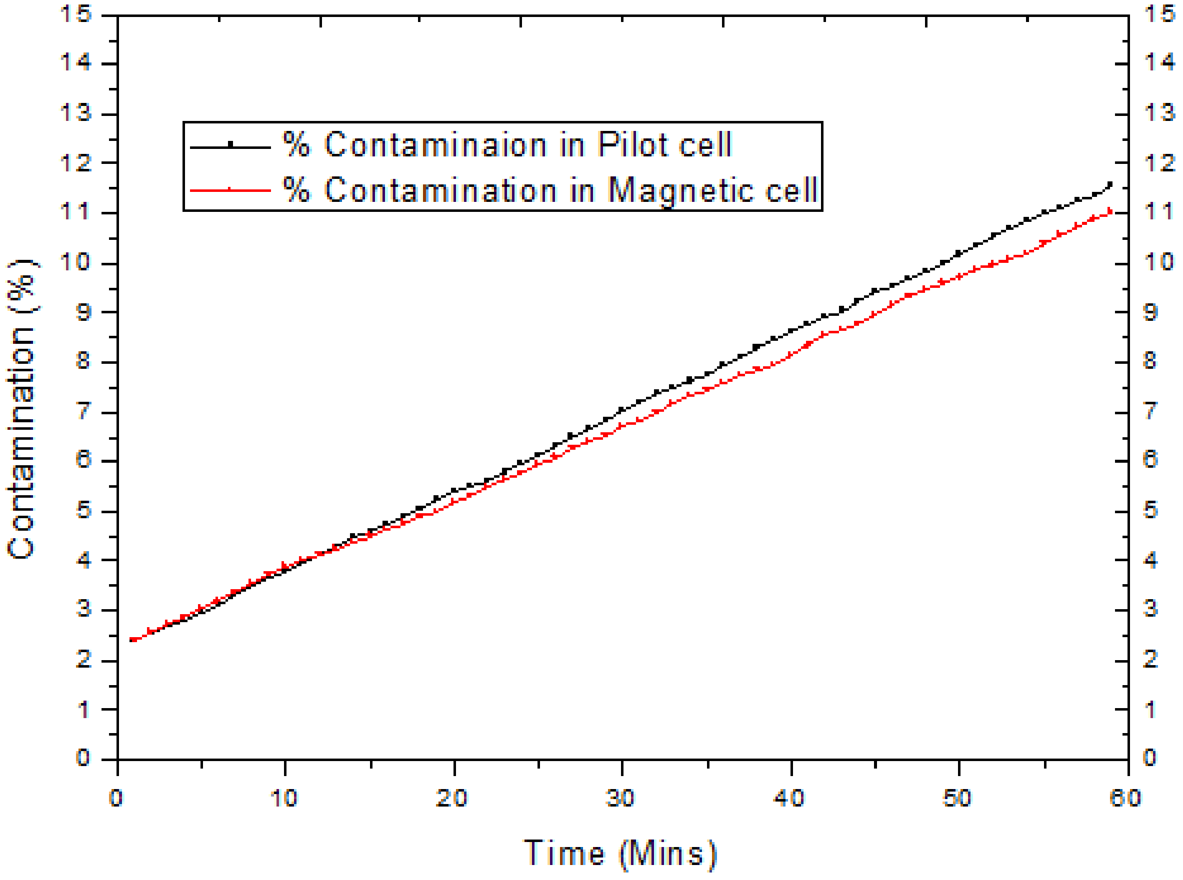

Figure 21 : Percentage cross mixing in pilot cell and cell with magnetic electrodes using a porous membrane.

It was observed that there is a clear performance difference when magnetic bipolar plates are used, but this might not be commercially exploitable.

However an interesting effect was noticed in the voltage efficiency of the system when cell voltage levels were recorded during the experiment. Figure 22 below shows the cell voltage comparison of magnetic cell and the normal cell during the duration of test. Same load was connected across the cell during the period and flow rates were kept at the same level. A slightly higher voltage was observed in the magnetic cell under load. Initially we suspected that this is due to the increase in the conductivity of bipolar electrodes due to the introduction of neodimum magnets, which are conductive.

But an increase in the voltage levels observed were quite random and there is a possibility that this is due to the magnetic attraction of paramagnetic species towards the electrodes. This was not the subject intended to be tested and therefore we were not in a position to carry out further testing to clearly identify this effect. But this seems to be an interesting affect to be further analysed at a later stage.

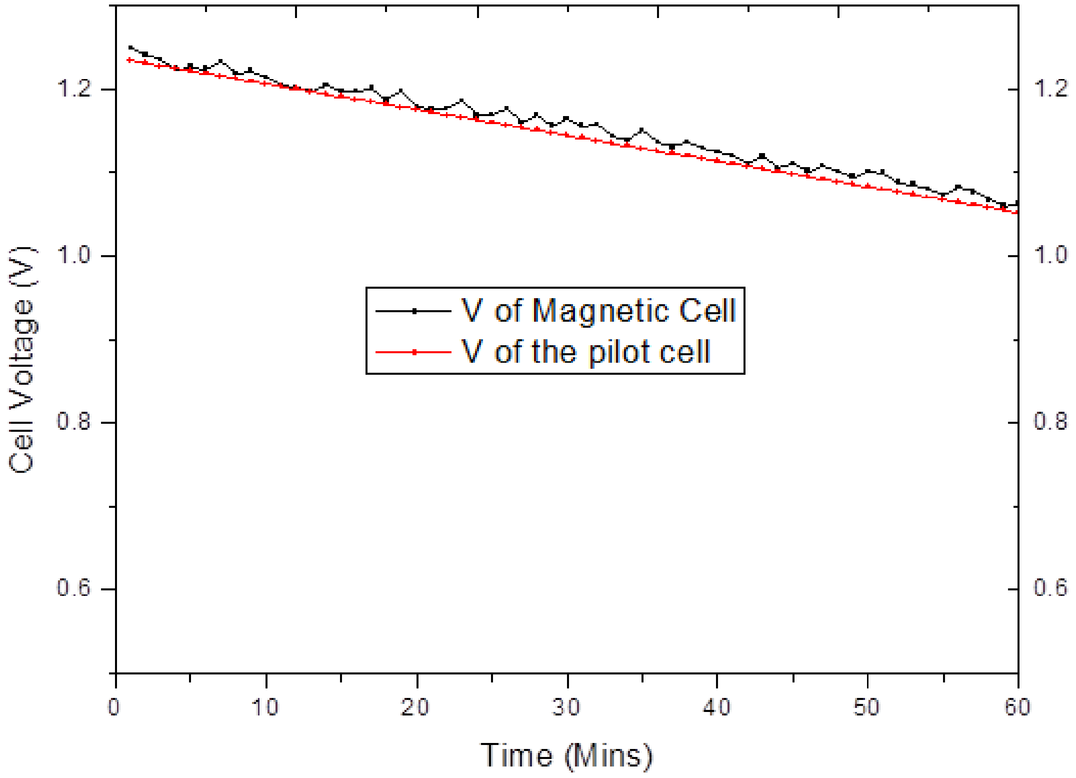

Figure 22 : Cell voltage performance of pilot cell and cell with magnetic electrodes using a porous membrane.

7.2.3 Testing the thermo-siphon assisted electrolyte pumping system

Heat powered pumping or thermosiphoning refers to the physical process of natural convection typically removing heat from a source and transferring it via fluid motion through a specific path to a heat sink. The buoyant flow arises from fluid density difference, which can be induced by the temperature difference in fluid.

It was proposed to use thermo-siphon assisted flow circulation system in the ELTUN to assist the pump. The heat generated by power electronic converter's semiconductor switches will act as the heat source, while pipes and large tanks will act as heat sinks. Tanks will be kept in a higher elevation compared to the converter and the semiconductor heat sink (heat source of the system). Figure 23 below shows the concept of the semiconductor heat assisted electrolytic pumping process.

During the testing process we identified that the main challenge is the identification of suitable electrolyte with optimum electro chemical properties and heat absorption properties. In addition the fluid has to have a low viscosity to enable efficient circulation.

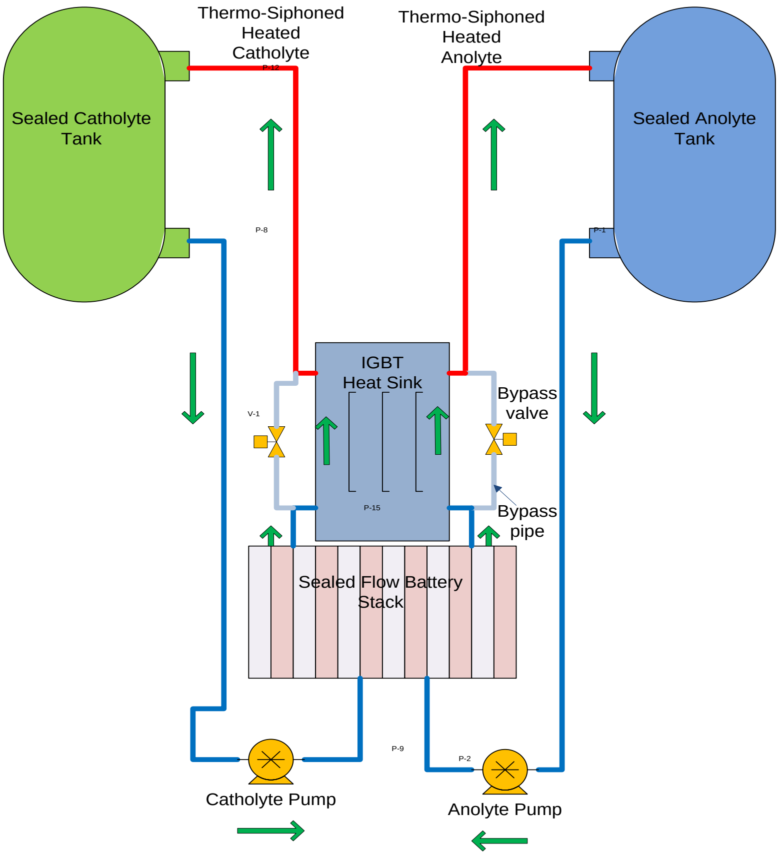

Figure 23 : Concept of thermos-siphon assisted electrolyte circulation

A small scale experimental set up was constructed to test the idea and the setup was able to successfully circulate electrolyte. Many electrolytes were tested for suitability to be used as a fluid in the thermos-siphon based electrolyte circulation systems. Electrolytes dissolved in solvents were first tested under these experiments. Few aprotic solvents tested other than water are 1,2 Dimethoxyethane, 1,3 dioxolane, tetrahydrofuran, tri ethylene glycol and tetra ethylene glycol.

After extensive testing, it was discovered that the heat absorption and thermal expansion properties of tri ethylene glycol and tetra ethylene glycol are ideal for these to be used in such a systems. Initially it was intended to use mica tubes as heat exchange tubes, but our cost calculations highlighted that such manufacturing (or using) such tubes for small scale production is not commercially viable. Copper tubes were used in the experimental setup and solvent based electrolytes were used to avoid copper corrosion.

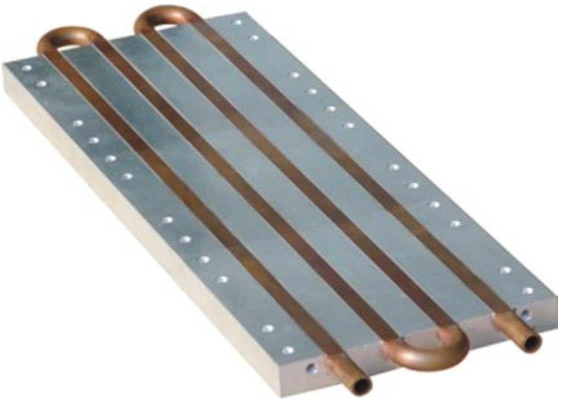

Figure 24 : Copper tubes embedded in aluminium heat sink

A Matlab based flow simulation model was developed to analyse the viability of a thermos-siphon based electrolyte circulation system for an energy storage in the power range of 2.5k-10kW. After final system a copper tube and Aluminium heat sink based thermosiphoning system was built in to the prototype power electronics.

7.2.4 Build and test the novel Dual Stage Cell Injection (DSCI) converter

Power Migration Partners had identified a novel bi-directional converter topology called Dual Stage Cell Injection (DSCI) converter which could work together with a flow battery system to allow power exporting to commence under low voltage input conditions.

One of the major problems with modern day grid tie inverters is that there is a minimum starting voltage which will enable inverters to start exporting energy. Typically this voltage could be 150V up to 300V DC. The main reason for this is that the DC link should get sufficient voltage to generate a sine wave using space vector modulation or other type of modulation technologies. DC bus voltage of around 400V DC is necessary for single phase 230V sine wave generation and for three phase system, this is close to 700V DC. The proposed PMP ELTUN has a unique property where it could intelligently combine the low input voltages from renewable energy sources with flow battery voltage in order to create necessary DC bus voltage. This allows the system to export power even if input energy levels are low. Figure 10 below is an illustration of the DSCI topology.

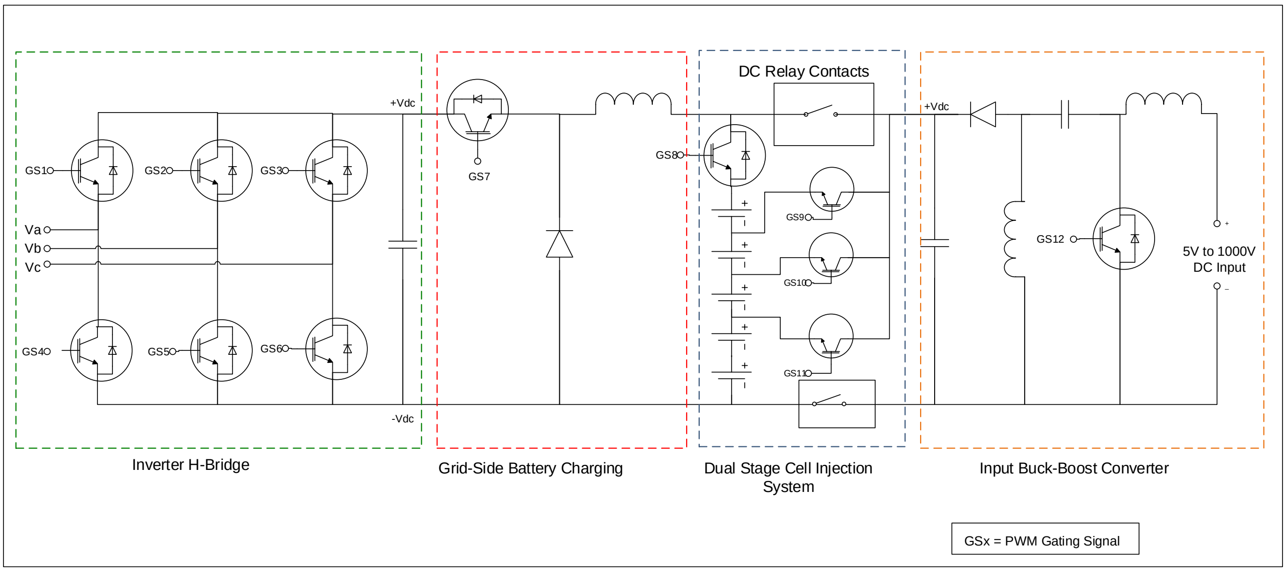

Figure 25 : SLD of the Dual Stage Cell Injection Converter

The new topology was designed with a common DC/DC buck-boost (Zeta) converter in the renewable source input side, which will accept 0-1000V, but it can start exporting power starting from 5V onwards. It works in two stages. First stage kicks in during low voltage input from 5V up to 175V.

When this mode is in control, the DC relay contacts will be open. The three small power semiconductor devices will be switched on and off to directly inject charging current in to different serially connected flow battery cell sections. For an example if input voltage is 10V, the buck boost converter will boost it to 30V and feed power to the flow battery through the bottom semiconductor switch in the DSCI subsystem. If the voltage is 80V, the buck boost converter will boost voltage up to 90V and inject current to the flow battery through the top semiconductor switch in the DSCI subsystem.

When the renewable source voltage is above 175V, this low voltage mode will be changed and the DC relay contact will get closed. During this short closing time, both sides of the DC relay will be kept in the same voltage level by intelligently using the flow battery voltage. Once the DC relay contacts are closed, the system will start operate in its second stage. Small semiconductor devices indicated in the DSCI subsystem will be completely bypassed in this stage. Voltage will be appropriately boosted or reduced (buck) to supply power in to the DC bus section (shown as grid side battery charging in figure 10). H-bridge inverter section will create three phase sine wave and export power out.

During battery charging from the grid, power will be drawn through the H-bridge and charge battery using the grid side battery charging section. DC relay contacts will open and all three small semiconductor switches in the DSCI subsystem will be switched off, isolating the renewable source side of the power converter. This function adds bi-directional function to the DSCI converter.

The benefits of this topology could be quantified using an example. A 22kW wave energy device designed by AlbaTERN uses an Aurora Grid tie inverter to export power at present. This inverter starts exporting power when the input voltage rises above 160V. According to generator characteristic table, when the voltage rises up to 158V generator should export close 3kW or in other words if the generator could be loaded, the wave energy device can deliver necessary torque to the generator to produce up to 3kW at 158V. But instead of generating power, the generator freewheels below 160V, because the Aurora inverter doesn't commence exporting energy below this voltage. Therefore if the wave energy resource is not strong enough to take the voltage above 160V (if height of the wave is not enough), the system will not export any power, even though the wave resource has power which could be converted to electrical energy, even at low wave heights. A typical percentage energy loss due to this effect can be calculated as follows;

Assume wave energy device produces average 11kW within a period of 8 hours and the system was operating under 160V for 2 hour during the 10 hour period in a day when wave resource is available. This is a typical wave resource availability pattern.

$$Maximum\ Energy\ Loss = \frac{3kW * 2h}{11kW * 8h + 3kW * 2h} \text{ x } 100\% \ = 6.38\%$$

But PMP ELTUN with be able capture this energy when the voltage level is below 160V and export it. With this special configuration PMP ELTUN has a strong advantage in the wave energy market compared to its competitors. Similar losses occur in Solar PV systems and small to medium scale wind turbines, but the loss of energy is not higher than 1%. In the case of solar PV, the Maximum Power Point (MPP) voltage of a solar PV panel at very low irradiance level is higher than 30% of the maximum irradiance level MPP voltage[7]. Therefore in solar PV, no significant advantage could be obtained by using this topology.

Due to the time limitation in this project, only a 4 switch H bridge was designed to export power to 230V AC systems. This needs a DC bus voltage of 400V which is achieved using the proposed topology. GaN devices were used for this design with reduced passive component size.

Schematic design was done initially and simulations were carried out to verify the performance and characteristics of the power converter topology. Pspice and sim power systems were used for simulations. Figure 26 below shows the schematic design of the GaN based inverter section of the power converter.

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[7] Bluepacific Solar module SW 245 - 255 poly / Pro-Series advanced data sheet.

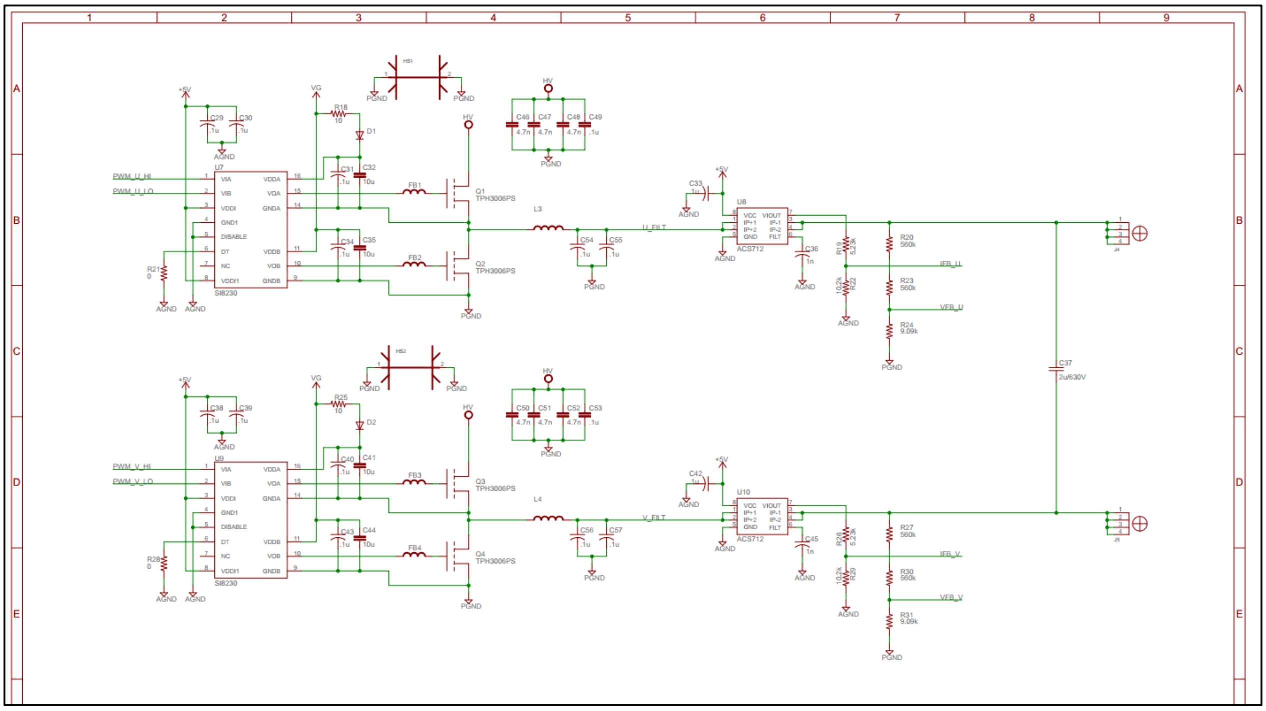

Figure 26 : Schematic design of the inverter portion of the power converter.

Layout was designed using the improved schematics and gerbers were generated for board manufacturing. Control card was purchased from Texas Instruments to save project time. The control of the system is based on Texas Instrument's C2000 Concerto family processor, which is a powerful controller specially designed for power electronics.

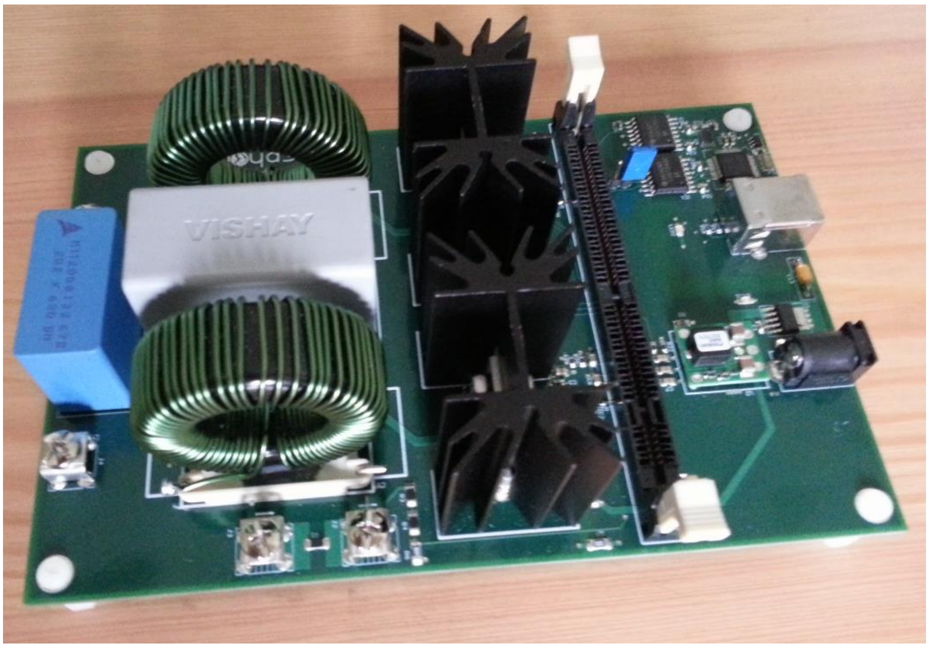

Figure 27 : Inverter portion of the power converter with GaN power switches

Figure 27 above shows the inverter portion of the power converter with GaN power switches. The DC input stage was developed as a separate unit in a different board for simplicity. GaN devices enables the system to be switched at 200kHz which helps to reduce the size of passive components such as inductors and capacitors.

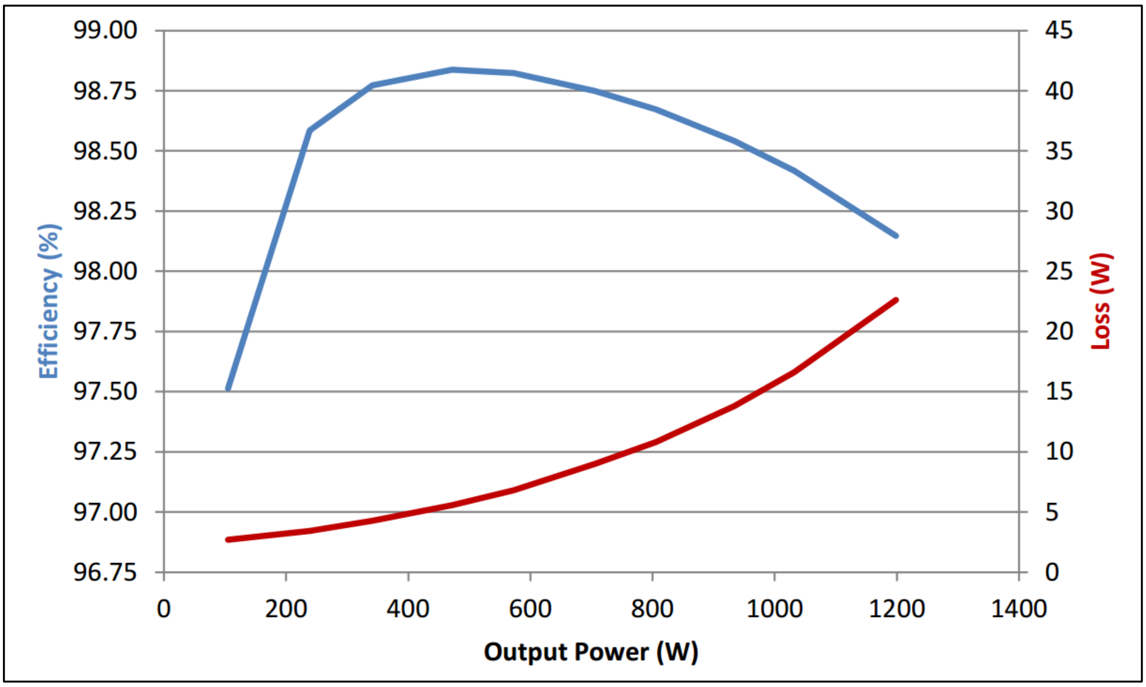

Figure 28 : Performance of the DSCI converter

This converter was tested up to 3000W of output power with forced cooling, even though it was a bit lower than the initially planned output. The converter worked stably up to 1250W without forced cooling. Figure 28 above shows the converter performance without forced cooling. As shown in the above plot, the system can be operated in efficiencies up to 98.75% a part load. We were able to achieve starting voltage of 20V and successfully export power. Therefore the converter design was successful but there's space for further improvement.

7.2.5 Identification of redox couples with optimum performance

This is the most challenging technical task tackled in this project is this task which enables to determine the best redox couple to be used in the flow battery. It is essential that the final flow battery design will be a product which can be commercialized. This can be achieved only if we can come up with a suitable redox couple which can eliminate disadvantages of the present day flow batteries developed by our competitors. Some key characteristics we compared in this stage were,

1. Ability to bring down cost by reducing material cost, manufacturing cost, maintenance cost and installation costs
2. Higher energy density than the present flow battery energy density of 20W/litre

3. Achieving true scalability. Present day flow batteries cannot be scaled down below 50kW, 500kWh in commercially viable manner due to use of large number of supporting components such as pumps, pipes and tanks.
4. Selecting a redox couple with wide operating window to match the weather of Knoydart peninsula.
5. Better voltage efficiency, better coulombic efficiency, wide operating temperature range and reduced hydrogen evolution.

An extensive study was done by amalgamating our extensive experience in electro-chemistry and inputs of external consultants. More than 4 PhD holders in the area contributed their expertise to successfully select a suitable redox couple.

Few considered redox couples were

1. Novel Lithium PAH and lithium poly sulphide based organic system.
2. Vanadium and ferrous based system with mixed aqueous sulphate, nitrate and chlorate media
3. Novel lithium polysulfide single liquid system

Out of all system the leading two options were option 1 and 3 above. Initial testing indicated that we can achieve 250Wh/ litre compared to 20Wh/litre in vanadium based systems. Since options 1 and 3 use lithium and sulphur as main material the system can be manufactured economically. Electrolytes for these selected options can be made using polar aprotic solvents, which enables the use of the thermos-siphon based electrolytic circulation system trialled out during this project. Out of option 1 and 3 , option 1 which is the novel Lithium Napthalate and lithium poly sulphide based organic system had a higher electrode current density close to 100mA/cm2. Therefore option 1 above was selected as the successful redox electrolytes for the final flow battery system. This system met the working temperature window which was required for successful operation in an environment such as Knoydart peninsula.

In the selected system, the anolyte consist of a solvated electron solution of Lithium ions. This is made by dissolving polycyclic aromatic hydro carbons in a suitable polar aprotic solvent and then solvating lithium metal in that solution. Catholyte is made by dissolving lithium polysulphide in the same polar aprotic solvent.

Figure 29 : Preparing Lithium Polysulphide in small quantities in the laboratory using a magnetic stirrer.

Figure 29 above shows preparation of Lithium Polysulphide in small quantities in the laboratory using a magnetic stirrer. Once the identified improvements were made, all characteristics were tested using a single cell prototype. Main flow battery characterization tests such as voltage efficiency tests, coulombic efficiency tests, capacity tests and accelerated cycling tests were carries out during this project. Some of the component integrity tests have to be carried out after the project period.

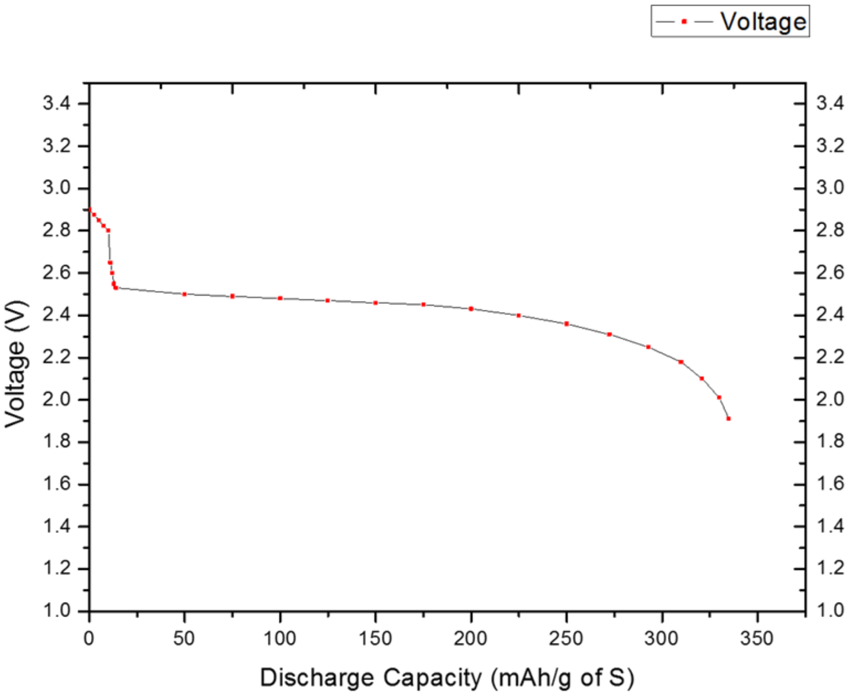

Figure 30 : Discharge capacity Vs Voltage curve

Figure 30 above shows the discharge capacity and the voltage change of a single cell using this redox couple. It was observed that this cell has a discharge capacity of 325 mAh per gram of Sulphur or close to 250Wh/ Litre. This is significantly higher than the all vanadium redox battery energy density of 25Wh/Liter.

7.2.6 Assembly and testing of the complete flow battery system

After carrying out improvement of battery separator and by adding additives to improve electrolyte performance, a significant increase in the cycle life was observed. Figure 31 shows the capacity degradation with battery cycling for the improved test cell.

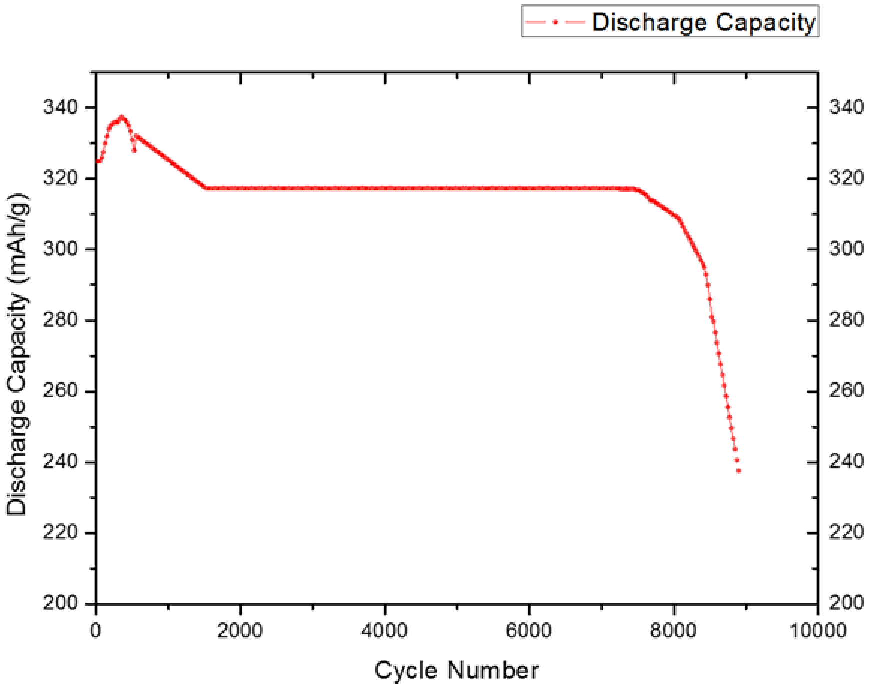

Figure 31 : Accelerated cycling test results for the improved test cell.

According to Figure 31 this improved flow battery cell can perform around 7500 charge-discharge cycles without a significant capacity loss.

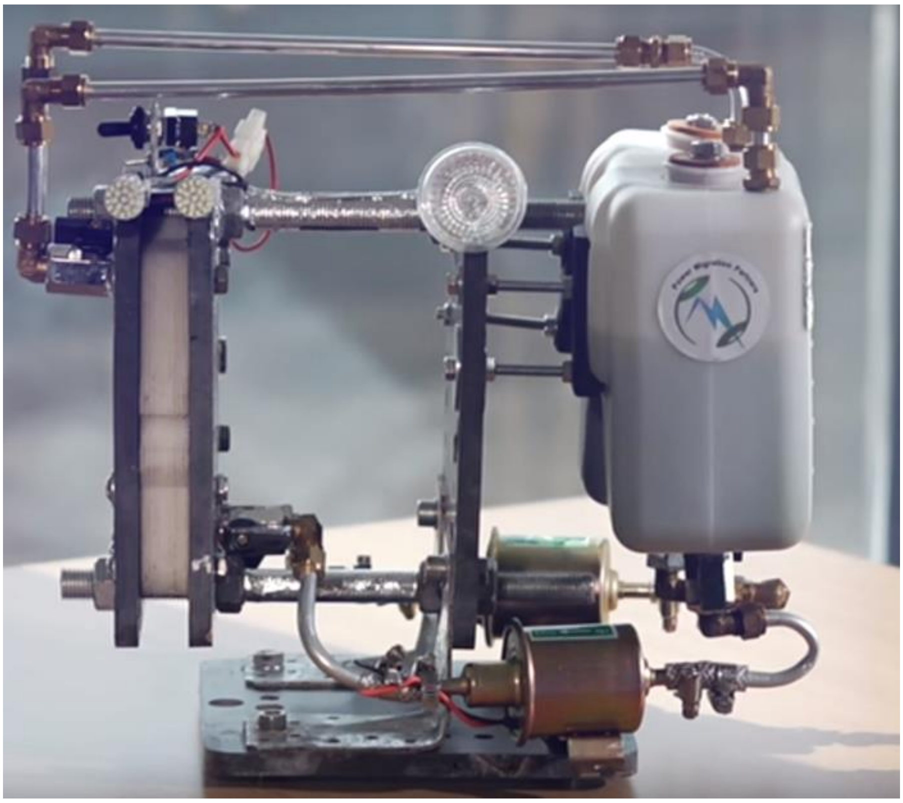

Figure 32: Assembled battery prototype.

Figure 32 above shows the assembled battery prototype. The load and generation profile identified in the Knoydart energy feasibility study was scaled down to a suitable level for this proto-type and tested to confirm the functional compatibility. A programmable Xantrex power supply was used to mimic the generator and a resistive load bank controlled by MOSFET was used as the load. Load and generation profiles were controlled by a LABVIEW interface.

These tests proved that the energy storage system will be able to stabilize the Knoydart grid. The energy storage system was programmed to act as a negative load as soon as the generator reached 80% of it's capacity. Artificially generated peak demands were successfully absorbed by the energy storage system together with the generator. Therefore the proto type was successfully used to show that the ELTUN energy storage system can be used to stablise the Knoydart micro grid.

8. TECHNICAL SPECIFICATION OF THE ELTUN FLOW BATTERY FOR KNOYDART

8.1 SYSTEM CONFIGURATION OF THE 400 KWH – 75 KW ENERGY STORAGE SYSTEM

Figure 33 shows the single line diagram of the proposed energy storage system installation. The shaded box on the left shows the smart energy storage and control systems with key component such as the flow stack, electrolyte tanks, pumps, flush tank, battery controls and the dosing unit. The shaded box on right shows the power converter, Power-Line-Communication system and the control unit. The power converter will be configured in a manner where it will be able to directly interface with a 415V 3-phase A/C distribution line.

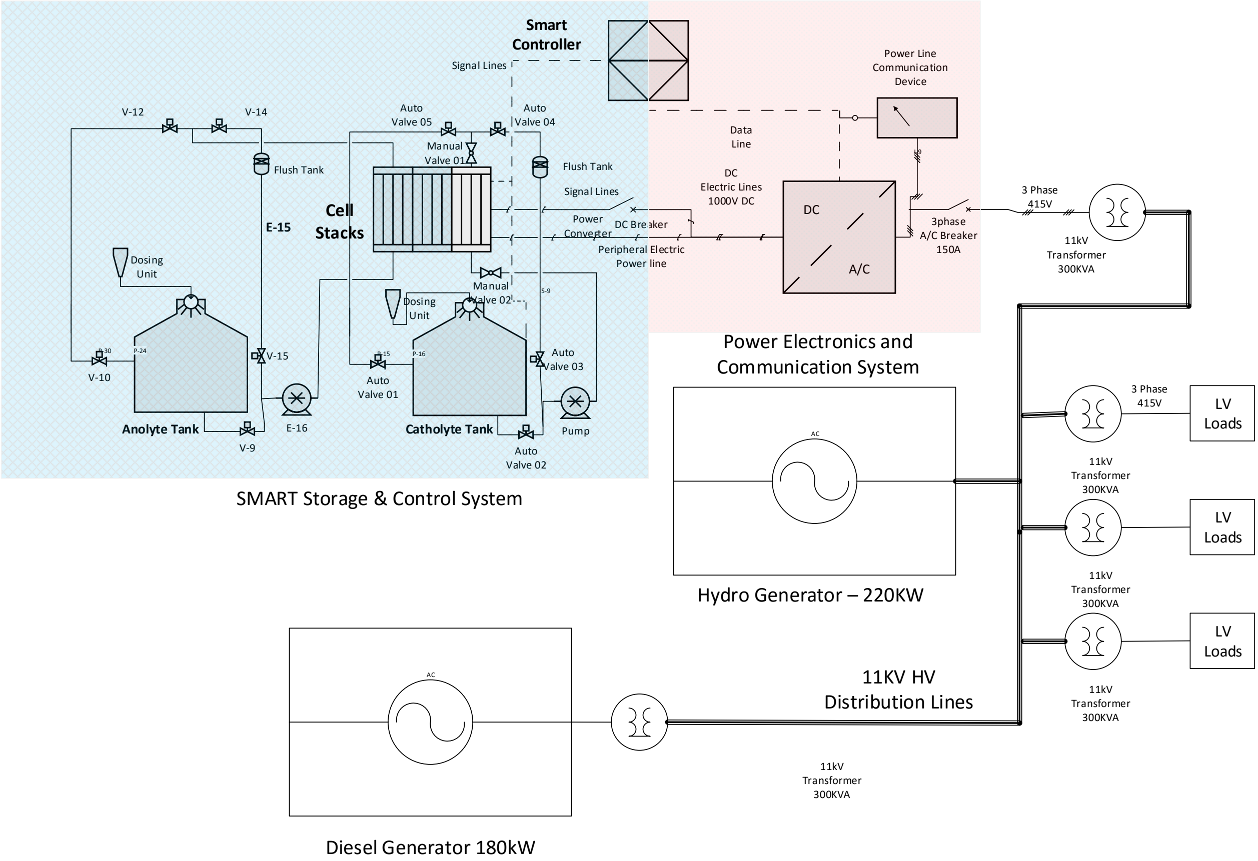

Figure 33: System SLD (Single Line Diagram) for proposed Knoydart energy storage system[8]

There will be multiple tanks of liquid storage which will have 2x 2000L tanks storing a maximum of 4000L of liquid. An area of approximately 2m x 2m will be required to accommodate these. If two tanks can be stacked on top of each other, the required foot print can be further reduced. It will be a plug and play system that can be connected to the Knoydart micro-grid using a simple air breaker and an isolator. The system can be removed or isolated simply using these isolation points. The system will be controlled using an embedded controller which will carry out two way communication using PLC (power line communication) and ethernet

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[8] : *Annex11 - SLD-Smart Flow Battery for Knoydart*

connectivity. Voltage, current, frequency, temperature, pressure and other monitoring will be done using embedded controllers.

As shown in Figure 34 below, the system has been designed to use an SMA sunny-island battery charging/discharging system that is specifically designed for micro-grids. An SMA multi-cluster distribution box will be used to integrate all generation equipment including the diesel generator as an emergency backup system. PMP's control system will maintain a bi-directional control communication link with the SMA multi-cluster box for stability. In addition, the PMP controller will communicate with various loads via existing PLC communication links. These inputs can be used to maintain the stability of the grid by injecting or extracting power from the grid.

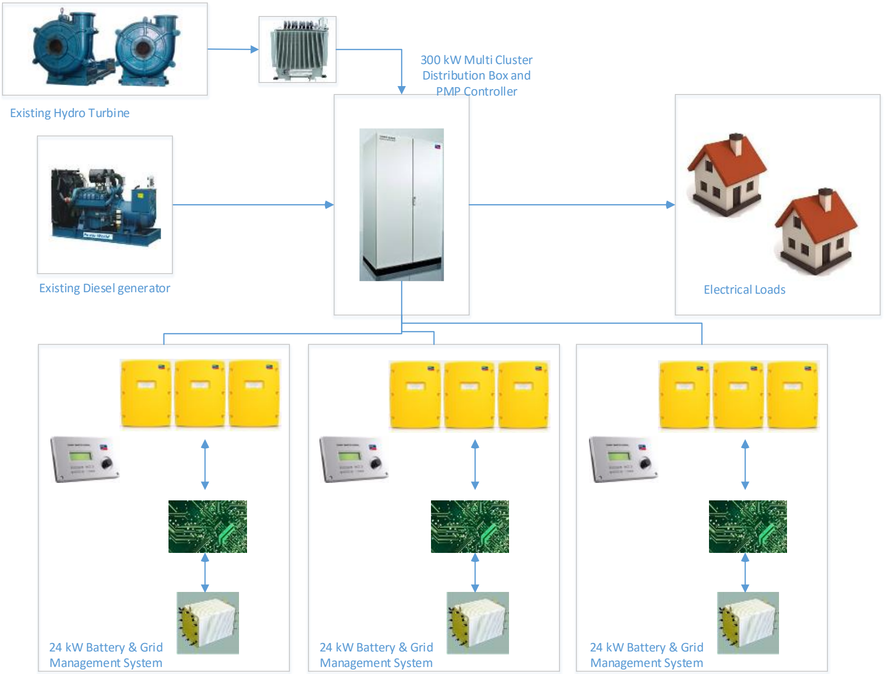

Figure 34 : Control system setup to maintain the micro-grid without disruption

9. RESULTS

The design and development of the ELTUN flow battery was successfully completed during this feasibility study. Many technical developments were carried out and a final battery stack was assembled.

Key ELTUN flow battery properties identified during the feasibility study are as follows;

Cell Voltage: 2 V

Round trip Efficiency: 90%

Repetitive Depth of discharge capability: 5%

Float Life: 25 years (Equivalent of 7500 cycles implemented in Knoydart Micro grid.

Cell stack replacement: 25 years (Based on accelerated cyclic testing)

Electrolyte replacement: 50 years (Based on accelerated cyclic testing)

After a detailed study it was identified that an ELTUN flow battery with 400 kWh of output capacity and 75 kW of output power will be able to cater for the future power demand profile of Knoydart while solving most of the existing grid related problems. The flow battery will charge itself during off-peak hours and support grid stabilization during peak hours by buffering the power supply. The power electronics will be continuously grid tied to the 415 AC system and avoid overloading of the hydro-generator by releasing power when the power demand passes a set threshold value. This will help to provide grid stability and reduce the number of black-outs.

System Description	Levelized Cost of Energy
Present energy generation with hydro scheme and diesel generator	13.7 p/kWh
Increased future demand with hydro scheme and diesel generator	16.3 p/kWh
Increased future demand with hydro scheme and ELTUN flow battery	12.4 p/kWh

Table 4 : LCOE (Levelized cost of energy) for a range of energy supply options

Table 4 above shows a comparison of levelized cost of energy with different options available to Knoydart Renewables. Use of ELTUN flow battery drives down the LCOE to 12.4p/Kwh compared to 16.3p/kWh, which will be the LCOE if the present system is used. Gird models used in the feasibility study clearly shows that ELTUN flow battery will be able to drive down LCOE of the Knoydart power generation and distribution system.